II universes, take $k \sim N\nu T/\omega^3$. Also, take $\nu \sim NT^{\alpha}$ where α is a constant; thus $N\sigma_e \sim N^2T^{\alpha+1}/\omega^2$. Suppose that $T \sim R^{-\beta}$ in the distant future. From equation (4), absorption is complete if $[4+(\alpha+1)\beta]n \leqslant 1$. Davies[2,6] investigated the thermal future of the universe by considering the interaction of the intergalactic medium with the cosmic electromagnetic blackbody background radiation. He showed that for models that expand more slowly than $t^{1/2}$, the intergalactic plasma eventually completely recombines; for models that expand more rapidly than $t^{1/2}$, the plasma does not completely recombine and remains coupled to the electromagnetic background radiation. If the intergalactic medium eventually recombines, then $\alpha = 1/2$ and $\beta = 2$; if the medium does not recombine, then $\alpha = -3/2$ and $1 \leqslant \beta \leqslant 2$. Thus, absorption of retarded gravitational waves in Class II universes is complete if $n \leqslant 1/7$.

Now consider advanced gravitational waves. Assume that σ_e approaches a constant as $\omega \rightarrow \infty$. In Class I universes, expression (5) shows that absorption is finite for all values of n. In Class II universes with a "hot big-bang", as they travel into the past, advanced waves that are not absorbed first eventually enter an epoch in which the cosmic matter is in thermal equilibrium with electromagnetic radiation at relativistic temperatures. As this epoch is entered there is a rapid increase in N because of thermal electron–positron pair production[7]; within this epoch the mass density of the cosmic medium varies as R^{-4}, but N still varies as R^{-3}. Thus full absorption of advanced waves occurs for $n \geq 1/3$.

Consider now condensed objects, and suppose that their interaction with gravitational waves can be represented by a constant σ_e. Suppose that in Class I universes there is a constant number density of such objects: for retarded waves absorption is complete; for advanced waves, absorption is finite. Suppose that in Class II universes the number density of condensed objects varies as R^{-3} in the distant future: absorption of retarded waves is complete for $n \leqslant 1/3$.

Assume, for the sake of argument, that the absorber theory of radiation is valid for gravitational waves, that only retarded gravitational waves can be observed in the actual universe and that σ_e saturates at high frequencies. In determining what cosmological models are to be eliminated, with these assumptions, as possible models of the Universe, the relevant values of n are those applicable for $t \rightarrow 0$ and for $t \rightarrow \infty$; such values will be denoted by n_0 and n_∞ respectively. No Class I universe with the characteristics taken above is eliminated. Class II universes with $n_0 > 1/3$ are eliminated. Class II universes with $n_\infty > 1/3$ are eliminated. In the standard "hot big-bang" model of general relativity, $n = 1/2$ in the radiation-dominated epoch so that this model has consistent advanced fields and is eliminated. In the spatially flat case of the Brans–Dicke cosmology, $n = (2\omega_{BD}+2)/(3\omega_{BD}+4)$ where ω_{BD} is a parameter; with[8] $\omega_{BD} \geq 0$ it follows that $1/2 \leqslant n \leqslant 2/3$, where the upper limit corresponds to the Einstein–de Sitter universe of general relativity: these models are eliminated since retarded fields are inconsistent. The Friedmann models with zero cosmological constant and negative spatial curvature have $n_\infty = 1$ and are hence eliminated.

Of course, these eliminations are purely hypothetical, being based on the three assumptions mentioned above. If cosmological observations were to establish one of these hypothetically eliminated models as a reasonable model of the Universe, then that result would constitute evidence against at least one of the assumptions.

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Solar test of Dirac's large numbers hypothesis

DIRAC[1,2] has proposed that the large dimensionless numbers that are constructable from the fundamental constants of physics and astronomy are related to each other, and are simple functions of our present epoch in the Universe. Thus he suggests that, as measured by atomic standards, the gravitational constant, G, varies with the time as t^{-1} and the number of nucleons in the Universe increases as t^2. In more recent work[3,4], he has pursued the consequences of assuming different modes of creation of new matter. We have found that Dirac's theory of multiplicative creation, but not his theory of additive creation, is not in contradiction with known facts about the Sun.

By "additive creation" he implies that matter is formed uniformly throughout space, and therefore mostly in intergalactic regions; the mass of a small object like a star would remain essentially unaltered by the new creation of matter. "Multiplicative creation" means that existing matter multiplies itself in proportion to the amount of matter already present; therefore the mass of a star, M, would grow as t^2.

In view of the important cosmological consequences of Dirac's theory, it is desirable to test it with methods presently available. One useful test object is the Sun. The proposed large change in G over the Sun's past lifetime and, with multiplicative creation, the concomitant large change in the Sun's mass, would be expected to produce a different evolutionary history for the Sun as compared with the 'standard' history computed on the basis of constant G and M. But with any theory the observable properties of the Sun today (mass, luminosity, and radius) must be achievable with 'reasonable' choices of initial chemical composition. Unfortunately, the chemical composition of the present surface layers, which presumably reflect the original composition, is known only with great uncertainty, and this allows a considerable latitude of choices. A further constraint (and a possible benefit that could accrue from a 'non-standard' theory) is the small solar neutrino flux that is observed and is not explained by 'standard' theories.

The one 'free' parameter in Dirac's theory is the age of the Universe, t_0, although observations of the Hubble constant put some limits on it. If t is measured from the time of formation of the Sun, then

$$G(t) = G_0\left[\frac{t_0 - t_\odot + t}{t_0}\right]^{-1}$$

and

$$M(t) = M_0\left[\frac{t_0 - t_\odot + t}{t_0}\right]^{n}$$

with $n=0$ for additive creation and $n=2$ for multiplicative creation. At the present epoch, $G_0 = 6.67 \times 10^{-8}$ cm^3 g^{-1} s^{-2}, $M_0 = 1.99 \times 10^{33}$ g, and $t_\odot = 4.5 \times 10^9$ yr.

The hypothesis of additive creation has already been tested by Pochoda and Schwarzschild[5]. They found that this hypothesis can be satisfied if $t_0 \geqslant 15 \times 10^9$ yr. Today, such an age for the Universe is certainly admissible, although it seemed rather too long a decade ago. But the required initial hydrogen content, $X = 0.81$, seems somewhat high. Moreover, the predicted brightness of the Sun in the past, in spite of the greater distance of the Earth from the Sun then (in the additive theory), may conflict with palaeontological evidence[6]. One further consequence of the additive theory is particularly relevant here: the hydrogen content near the centre of the present Sun must be completely exhausted. Although Pochoda and Schwarzschild did not publish any temperatures, the central temperature of their final model is probably about 19×10^6 K (see, for example, ref. 7). In these conditions the expected neutrino flux must be enormous—several orders of magnitude greater than the upper limit of the neutrino flux measured by Davis[8]. But it should be borne in mind that standard solar models themselves predict a neutrino flux that is about an order of magnitude larger than Davis's upper limit of 1 SNU.

In order to test Dirac's hypothesis of multiplicative creation, we have evolved several sequences of stellar models up to the present age and mass of the Sun. It has been assumed that, since the solar gases are highly ionised, new ions (and a corresponding number of electrons) are created in the vast empty spaces between the existing particles. They are assumed to be of the same species as their 'parent' ions. Moreover, they must share the same kinetic energy and linear momentum as their neighbours, on the average, and therefore units of kinetic energy and momentum (including units of rotational angular momentum of the whole Sun) must also be created. Dirac has already postulated these conditions for the Earth, in order not to contradict geological evidence. For our purposes, it is sufficient merely to scale up the chemical structure of the evolving solar models as the mass of the Sun is increased. For simplicity, axial rotation of the Sun is neglected.

The other physical input parameters are the same as those used in previous work[9]. To summarise them here for convenience, we have adopted: the new Carson (unpublished) opacities, which are very close to those of Cox and Stewart[10] for main-sequence stars of low and intermediate masses; the nuclear cross sections of Bahcall, Bahcall and Ulrich[11], but with the neglect of the *pep* reaction; a ratio of mixing length to pressure scale height in the outer convective envelope equal to $\alpha = 2$; and a metals abundance of $Z = 0.015$. Results for the initial and final solar models are given in table 1. We have found that the final radius does not agree exactly with the observed radius, for the choice of $\alpha = 2$. But, as many people have shown a suitable change of α can achieve agreement between the radii without significantly altering the luminosity, which is affected primarily by the choice of initial chemical composition. Therefore, we have not considered it worthwhile to rerun the sequences with different guesses for α until the final radii are correct.

The standard solar model obtained here is very similar to the analogous one already calculated by Carson, Ezer, and Stothers[9]. The two models are not identical because we have here adopted equilibrium nuclear reaction rates and a slightly different treatment of the thermodynamical quantities, apart from the fact that the computer program itself is different.

Turning now to the final solar models based on Dirac's multiplicative theory, we find the rather surprising result that they are nearly the same as the final model based on standard theory! This occurs in spite of the widely disparate initial masses, occasioned by the use of a full range of choices for t_0. The reason for this similarity is that the effect of a larger G in the past is to increase the luminosity[6], whereas a lower stellar mass decreases it. As a result of these compensating factors, the ratio L/M remains approximately constant. Since the nuclear reaction rate and the amount of hydrogen depletion depend on the L/M ratio[12], the final central temperature and the final hydrogen profile throughout the Sun are about the same as they were in the standard case.

Table 1 Final models for the present Sun based on Dirac's theory of multiplicative creation

Case	Standard	1	2	3
t_0 (10^9 yr)	—	20	10	7
Initial G/G_0	1	1.29	1.82	2.80
Initial M/M_0	1	0.60	0.30	0.13
X	0.758	0.755	0.751	0.749
Z	0.015	0.015	0.015	0.015
Initial log $L/L_\odot$	−0.13	−0.43	−0.83	−1.35
Initial log T_e	3.73	3.71	3.67	3.62
Final X_c	0.40	0.43	0.45	0.47
Final T_c (10^6 K)	15.2	15.1	15.1	15.0
Final ρ_c (g cm^{-3})	151	144	140	133
Neutrino flux (s.n.u.)	~7	~6	~6	~5

Since the radius, r, of the Earth's orbit around the Sun increases, in Dirac's multiplicative theory, as t, the temperature of the Earth's surface may be expected to change like $(L/r^2)^{1/4} \sim$ constant. This naive prediction is not in contradiction with palaeontological evidence. But why are well-preserved Precambrian and early Cambrian fossils in essentially perfect shape if their masses have increased by a significant percentage?

One could pursue the test of Dirac's theory by constructing theoretical isochrones for old clusters containing stars of low mass and comparing them with observed cluster H–R diagrams. Although we have not done this, it is interesting that the more massive members of this old population must have evolved long ago—mostly into white dwarfs, initially. But since the upper mass limit for a stable white dwarf (or neutron star) is proportional to $G^{-3/2} \sim t^{3/2}$, and since the mass of the star itself increases as t^2, eventually these stars will all undergo gravitational collapse. The galactic halo must be popping with continually forming black holes. The ultimate cosmological consequence is a universe full of gravitationally collapsed objects.

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Age and rates of denudation of Trap Series basalts at Blue Nile Gorge, Ethiopia

BETWEEN Lake Tana and the Sudan border the Blue Nile has cut a deep gorge across the Ethiopian Highlands. The first 150 km of its course lies on lavas of the Tertiary Trap Series, after which the river flows through horizontal Mesozoic and Palaeozoic sediments until the Precambrian is reached 330 km from Lake Tana[1]. About 280 km below the lake the Addis Ababa–Debre Markos road crosses the gorge at 10° 05′N, 38° 10′E, where 250 m of Trap Series basalts overlie at least 1,150 m of sediments the base of which is not exposed. The gorge is 1,400 m deep and 20 km wide and is incised into a plateau 2,600 m high.

On the south side of the gorge the Trap Series section comprises at least five thick horizontal flows of aphanitic basalt, belonging to the lower part of the Trap Series as a whole. The top three flows are well exposed and each is several tens of metres thick and extends laterally for over